CHAPTER 4

Instrumentation

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INSTRUMENTATION

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OVERVIEW

The purpose of instrumentation in electromyography (EMG) is to preserve information contained in the bioelectric activity associated with the initiation and regulation of muscle contraction. Relevant questions to ask at the outset of any investigation using (EMG) are about what information can be obtained by this measurement and how that information relates to the purpose of the ergonomic study. This chapter discusses the instrumentation requirements necessary for obtaining information from the EMG signal. Chapters 5 through 7 will elucidate further on how this information may be used in questions relating to ergonomics.

To provide a framework for the discussion of EMG instrumentation, the information obtainable from the EMG can be divided into the following three general categories.

1. The relationship between temporal aspects of EMG and anatomically associated movement.
2. The relationhip between EMG and the production of force.
3. The relationship between EMG and muscle fatigue.

Each of these categories requires the EMG signal to be processed in ways that preserve the signal information necessary to accomplish the aim of the measurement.

ELECTROMYOGRAM SIGNAL INFORMATION

To respond definitively to the questions posed above requires a complete accounting of the contribution of the many and interrelated factors that influence the signal characteristics of the detected EMG. Researchers have developed mathematical models relating selected factors and have compared their behavior to empirical observations.[1-3] Although no current scientific consensus on a comprehensive model exists, work in this area has revealed many important relationships. Until the effect of factors such as velocity, acceleration, and type of muscle contraction are more fully understood, the interpretation of information obtained from the EMG signal will be clouded in uncertainty. What can be concluded from a review of Table 4-1 is that the detected EMG contains information about not only the anatomic, physiologic, and neurogenic factors that shaped the waveform, but about a host of other factors that distort this information.

Clearly, not all information contained in the signal is needed to answer every research question regarding muscle activation. Perhaps the first step in the formulation of a measurement question using EMG is to decide what information is needed from the signal to satisfy the purpose of the investigation. The discussion that follows will divide the information into three general categories based on their wide use and general acceptance. This treatment should not be considered an implied limitation on other viable uses.

Temporal Information

The most basic information obtainable from an EMG record is whether the muscle was on or off during an activity or at a particular point in time. For EMG to be on, it must exceed a threshold, whether defined by an arbitrary or statistically predetermined level or by the noise level of the equipment responsible for the measurement. It often is more difficult to determine that a muscle is off because a muscle may infrequently be in a state of total relaxation. In such cases, the threshold must be set high enough to avoid false on conditions. In the context of temporal measurements, the goal of the information gathering process is to determine, with as much precision and sensitivity as practical, the point in time the muscle was activated or deactivated. The appropriateness of signal processing methods must be evaluated with this goal in mind.

EMG-Force Information

Perhaps the most used and abused category of EMG information is in the measurement applications that relate the EMG detected at a muscle site to the resultant force or torque generated by the muscle. The popularity of these applications are due to the potential value of the information obtained. For example, in ergonomic studies, potential applications include the use of EMG to evaluate tool use and worker postures in the prevention of work related injuries.

An EMG-force measurement seeks to quantify the average number and firing rate of motor units contributing to a particular muscle contraction, and to relate the quantity to the actual force produced. A number of assumptions are implicit to the validity of the measurement application. These are detailed in Chapter 6. Of

TABLE 4-1

Factors That Influence the Signal Information Content of Electromyography

Factor	Influence
Neuroactivation	— the firing rate of motor unit action potentials — the number of motor units recruited — synchronization of motor unit firings
Muscle fiber physiology	— the conduction velocity of muscle fibers
Muscle anatomy	— the orientation and distribution of muscle fibers of motor units — the diameter of muscle fibers — the total number of motor units
Electrode size and orientation	— the number of muscle fibers within the pickup area of the electrode — the number of motor units within the pickup area of the electrode detection surface relative to the muscle fibers
Electrode-electrolyte interface	— material and preparation of electrode and electrode site — electrode impedance decrease with increasing frequency (high-pass filter)
Bipolar electrode configuration	— effect of distance between detection electrodes and bandwidth (bandpass filter) — the orientation of detection electrodes relative to axis of muscle fibers

primary importance is the degree to which the muscle site being monitored is representative of the muscle as a whole. Also crucial is that the relationship between the measured quantity and the resultant force be known a priori for the actual conditions of the measurement (eg, isometric versus isotonic, concentric versus eccentric, the position of the joint). A linear relationship should not be assumed. The degree of controversy surrounding this relationship suggests that the relationship be determined for each subject and measurement situation.

The aim of signal processing in this category of measurement is to assign a numerical value (usually a percentage of a maximum voluntary contraction) to the level of EMG activity associated with the generation of a corresponding force. With the increasing intensity of a contraction, more and more units are recruited, and the unit firing frequency increases. The summated motor unit activity reflects these changes as the resulting interference pattern becomes more dense and of greater amplitude. Signal processing methods attempt to quantify the general character of these changes by some form of averaging.

EMG-Fatigue Information

The third category of information obtainable from the detected EMG signal may be used to identify the occurrence of localized muscle fatigue. A host of investigators have demonstrated a decrease of power density in the high frequency region of the EMG signal and an increase in the low frequency region during fatiguing contractions.[4-7] Lindstrom et al have demonstrated that the frequency shifts were almost entirely dependent on the propagation velocity of the action potentials.[8] The reduced propagation velocities have been linked to the production and accumulation of acid metabolites.[9]

The median or center frequency of the power density spectrum is the variable usually used to characterize the frequency shift linked with fatigue. Figure 4-1 is an idealized version of the frequency spectrum with the median or center frequency indicated. Lindstrom et al have demonstrated that the center frequency of the power spectrum is proportional to propagation velocity.[8] Lindstrom and Petersen have shown that decreases in center frequency during isometric and isotonic contraction follow approximately exponential curves characterized by their time constants.[10] Figure 4-2 graphically illustrates the dependence of the power spectrum on the developing fatigue.

CRITERIA FOR THE FAITHFUL REPRODUCTION OF THE EMG

To gain an appreciation of how information is encoded in a complex waveform and better understand the technical specifications required of processing

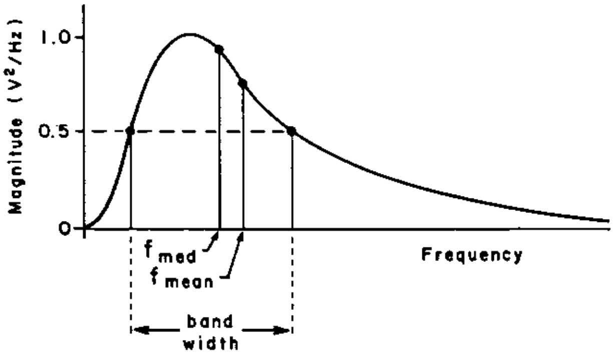

FIGURE 4-1

An idealized version of the frequency spectrum of the EMG signals. Three convenient and useful variables are indicated: the median frequency, f_{med}; the mean frequency, f_{mean}; and the bandwidth.

Reprinted with permission from Basmajian JV, DeLuca CJ: Muscles Alive: Their Functions Revealed by Electromyography, ed. 5. Baltimore, MD, Williams & Wilkins, 1985, Figure 3-16, p 99.

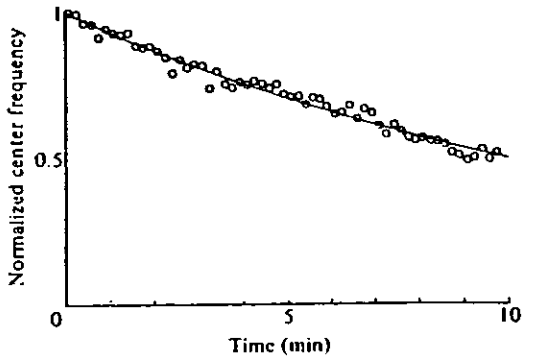

FIGURE 4-2

Dependence of the power spectrum on the developing fatigue. Signals from a masseter muscle under a constant biting force of 30 N.

Reprinted with permission from Lindstrom L, Peterson I: Power spectra of myoelectric signals: Motor unit activity and muscle fatigue. In: Stalberg E, Young RR (eds): Clinical Neurophysiology. London, England, Butterworths Publishers, 1981, Figure 4.6, p 75.

instrumentation, a brief discussion of the content of the EMG signal will prove useful.

EMG Signal Characteristics

Factors influencing the peak-to-peak amplitude of the detected EMG include the number and size of active muscle fibers, the size and orientation of the electrode detection surfaces relative to the active muscle fibers, and the distance between the active fibers and the detection electrodes. The frequency content of the EMG also is influenced by factors such as the size and distance between electrodes and the distance between the active fibers and the detection electrodes. The confluence of these factors makes it impossible to specify a definitive peak-to-peak amplitude and signal frequency range. The Ad Hoc Committee of the International Society of Electrophysiological Kinesiology (Appendix B), however, has published the following typical ranges for surface electromyography: amplitude range (mV) 0.01–5; signal frequency range (Hz) 1–3000.

EMG Represented by a Power Spectrum

The detected EMG is a dynamic analog signal in which the value or magnitude of the waveform varies with time. In contrast to a steady direct current signal which may contain a single piece of information, a dynamic analog signal continuously varies in magnitude and thus information content. The amount of information that may be transmitted or communicated in a segment of time is determined by the maximum rate of change in the signal amplitude. The power density spectrum of a signal is a unique way of representing the relationship between the signal amplitude and the signal rate of change or frequency.

The Fourier transform used to compute the power density spectrum is a mathematical technique by which any signal may be expressed as an infinite sum of sinusoidal components. The relative frequencies and phases may be combined to represent, exactly, the original signal at each instant in time. Although the theoretical number of sinusoidal components summed is infinite, the contribution of higher order components becomes smaller and smaller until they are unrecognizable from noise. This may occur after only a few harmonics or after 100, depending on the shape of the waveform. Figure 4-3 illustrates the power density spectrum of EMG recorded from bipolar surface and indwelling electrodes. Note that the spectrum extends from 10 Hz to about 400 Hz for surface electrodes and from 10 Hz to about 1000 Hz for indwelling electrodes. The lower frequency content of the surface electrode spectrum is consistent with the narrower bandpass characteristic typical of bipolar surface electrodes having greater interelectrode distances.

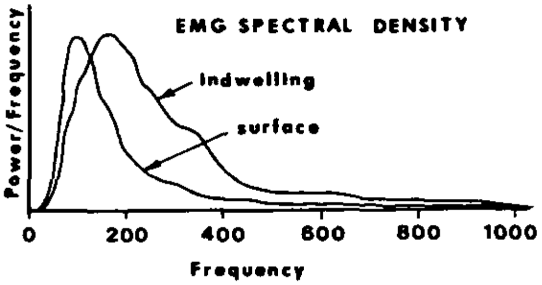

FIGURE 4-3

Frequency spectrum of EMG as recorded via surface and indwelling electrodes. Higher frequency content of indwelling electrodes is due to closer spacing between electrodes.

Reprinted with permission from Winter DA: Biomechanics of Human Movement. New York, NY: John Wiley & Sons Inc, 1979, Figure 7.5, p 135.

Amplitude Linearity, Phase Linearity, and Bandwidth

To preserve the original information content of the detected EMG requires any EMG instrumentation to possess amplitude linearity, phase linearity, and adequate bandwidth.[11] Amplitude linearity dictates that the ratio of input to output voltages be a linear function within the working voltage range of the instrument. Bandwidth, or frequency response, refers to the requirement that the amplitude linearity be extended to all frequencies within the working frequency range of the instrument. The logic of this requirement may be understood easily by referring to the Fourier spectrum in Figure 4-3. For the information in the original waveform to be preserved, each individual frequency component of the signal must be treated similarly, lest the instrument output signal spectrum change its shape. It should be obvious that any change in the shape of the frequency spectrum as a result of signal processing constitutes a distortion from the original waveform. Likewise, phase linearity requires that the phase relationship of each frequency component at the output of an instrument be identical to the phase relationship that existed at the input.

Noise

If the signal detected at the electrode site contains information only relevant to the purpose of the measurement, and nothing is done to alter this information during signal amplification and processing, the precision and accuracy of the measurement is determined by the recording or output reading device. This is a description of an ideal measurement system, not realizable in EMG instrumentation.

In addition to the desired EMG signal not being the only signal detected at the electrode site, it contains much less signal power than other extraneous signal sources commonly present. Noise is defined as any extraneous or unwanted signal that interferes with the transmission of the correct information. Noise is present and is introduced to the relevant information at the muscle site and during signal amplification, processing, and recording. Chapter 3 contains a discussion of the common artifacts seen during EMG recordings. Because the EMG signal information becomes mixed with the noise information, the signal-to-noise ratio is the single most important factor in judging the quality of the information obtained.

Equally significant are those noise sources generated by the equipment used to detect, amplify, and record the EMG. All conductors exhibit some resistance to current flow and, therefore, generate thermal noise. Thermal noise is generated by the random movement of electrons and other free carriers and is a consequence of the Second Law of Thermodynamics. The thermal noise voltage is dependent on the resistance of the material, the temperature, and the bandwidth, according to the equation:

$$V^2\,(\mathrm{RMS}) = 4\ \mathrm{KTRB} \qquad (1)$$

where K is Boltzmann's constant; T is temperature in degrees Kelvin; B is bandwidth in hertz; and R is the resistance in ohms. Because of the randomness of the noise voltage, the Fourier spectrum extends from DC to infinity. Thermal noise is generated in the electrodes, in the wire leads connecting the electrodes to the amplifier, and in the host of electronic components internal to the EMG instrumentation.

Because of the limited bandwidth required of EMG instrumentation (less than 10 kHz), 1/f, or flicker noise, plays a dominant role.[12,13] As the name 1/f implies, flicker noise decreases with increasing frequency, being of little consequence above 1 kHz. Flicker noise is associated with semiconductor junctions and certain types of film resistors, the DC level of which depends on the energy level at which the junction or film component is operating.

Of particular significance in EMG is the motion artifact that may result from a movement disturbance of the electrode-electrolyte interface. As previously discussed, a charge gradient exists at the electrode-electrolyte interface and any relative movement at the interface will alter its capacitance. This has the effect of redistributing the charge at the interface, thus producing an input current to the amplifier. The resulting voltage artifact is a low-frequency randomly occurring noise source that is very troublesome. Another type of motion artifact is generated by the movement of the wire leads connecting the electrodes to the amplifier. These artifacts are induced into the wires through electromagnetic induction, the method used to induce alternating voltages in electrical generators.

Although motion artifacts are at the low end of the EMG signal spectrum (less than 30 Hz), they often are of sufficient amplitude to be difficult to remove with simple high-pass filters.

ELECTROMYOGRAPHIC AMPLIFIERS

The standard processing component in any EMG instrumentation system is the amplifier. Actually, the amplifier normally is composed of several stages of amplification, the most important of which is the first stage or preamplifier. Together the stages perform several important functions including 1) isolation between the signal source and recording instrumentation, 2) current to voltage conversion, 3) voltage gain, and 4) noise reduction.

The two most important characteristics of an EMG amplifier are high input impedance and a differential input. These characteristics translate into two important benefits: conservation of signal power and reduction of noise power.

Conservation of Signal Power

The need to isolate the signal source from the recording instruments can best be understood by considering the power of the signal source. Signal power is defined as the signal voltage squared divided by the source impedance. The object of amplification is to increase the signal power to a level necessary to drive recording devices. This requires the efficient transfer of power between the signal source and preamplifier. Any increase in the impedance of the source will reduce the power available for transmission. Clearly, the reduction of source impedance is advantageous. This may be accomplished in two ways. First, steps should be taken to reduce factors contributing to the source impedance, such as abrading the electrode site with an abrasive to reduce the skin resistance. The second primary method, however, is to reduce the effective source impedance by isolating the source from the load.

Isolation is accomplished by buffering the source with an amplifier exhibiting a large input impedance and a small output impedance. For the purpose of illustration, the transmission link can be viewed as a signal source in series with two lumped impedances as in Figure 4-4. One impedance is used to represent the source impedance, made up of the combined tissue, skin, and electrode-electrolyte impedances. The other impedance represents the input impedance of the preamplifier. Together they form a voltage divider. The magnitude of the voltage drop across each lumped impedance is proportional to the fraction of each impedance to the total impedance. Thus, the larger the source impedance, the larger the fraction of the total voltage dropped at the source.

In the illustration, any voltage drop across the source impedance represents signal power that is lost. By increasing the size of the input impedance, the percentage of power lost is decreased, thus increasing the efficiency of the transmission. The high input impedance of the amplifier coupled with its low output impedance has the desirable characteristic of lowering the effective source impedance while preserving the signal power.

The actual magnitude for input impedance desirable for high fidelity amplification depends on the size of the source impedance. A good rule of thumb is that the input impedance be 100 times larger than the source impedance. For a typical value of surface electrode impedance (impedance measured between the detection electrode) of 20 kΩ, an input impedance of 2 MΩ is desirable. This impedance is easily obtainable with solid state amplifier designs.

A common error made by persons unfamiliar with electronics is to assume that the published input impedance specification extends over the total bandwidth of the amplifier. This is not the case, however, because even small amounts of capacitance in parallel with the input resistance will significantly reduce the input impedance at 100 Hz. This problem is exacerbated by the capacitance of the input lead wires, their capacitance often being many times the input capacitance of the amplifier itself. To prevent confusion, the input impedance should either be specified as an equivalent parallel combination of resistance and capacitance or specified at a representative frequency within the usable bandwidth. A reasonable frequency for surface recording is 100 Hz.

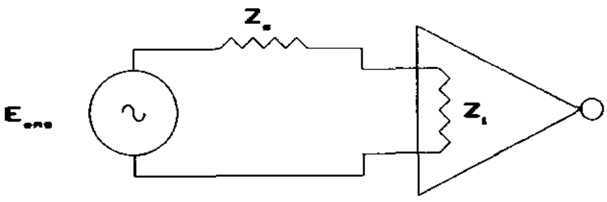

FIGURE 4-4

Simplified circuit of bioelectric generator to amplifier transmission link. Zs represents the lumped impedance of the source to include the complex tissue, skin, and electrode-electrolyte impedances. Zi represents the input impedance of the amplifier.

Noise Reduction

Conserving as much of the power of the EMG signal source in the transmission to the preamplifier is one way of dramatically improving the signal-to-noise ratio. Another approach is to reduce the noise power.

For those noise sources that are external to the amplifier, the most potent method of noise reduction is through the common mode rejection property of the differential amplifier. In such a circumstance, the differential amplifier amplifies only the difference voltage between its two input terminals. Any signal voltage common to both input terminals, each referred to a common reference terminal, should ideally produce a zero output. The degree to which this ideal is realized in practical designs is designated by the common mode rejection ratio (CMRR), defined as the difference signal gain divided by the common mode signal gain. As such, the CMRR specifies the improvement in the signal-to-noise ratio that will occur, after amplification, as a result of common mode noise sources. The International Society of Electrophysiological Kinesiology (ISEK) recommends the preamplifier CMRR be greater than 90 dB.[14] The decibel notation is commonly used to express voltage ratios. The conversion is as follows:

$$\mathrm{CMRR(dB)} = 20 \log_{10} \mathrm{CMRR} \qquad (2)$$

Because the CMRR is influenced by both frequency and gain of the preamplifier, a more meaningful specification would relate the CMRR to a specific input frequency and preamplifier gain, if variable.

In practical EMG measurement applications, including those in ergonomics, the CMRR of the preamplifier is never realized because of the unequal source impedance seen by each input terminal. This is due, primarily, to unequal electrode impedances. The effect of the so called **source impedance imbalance** is to create an unequal voltage drop across each electrode impedance. The different voltage drops creates an artificial difference signal that is indistinguishable from any other difference signal. Thus, it will be amplified by the difference signal gain, the effect of which is to reduce CMRR. It should be emphasized that it is not the absolute value of source impedance that determines the reduction in CMRR but rather the difference as seen from one input terminal compared with the other.[13] Because the source impedance forms a voltage divider with the input impedance, increasing the input impedance will greatly reduce this problem.

Reasonable precautions should be exercised to reduce the level of noise seen by the preamplifier. These include avoiding the location of interfering equipment, shielding of the input cables and preamplifier, and locating the reference electrode judiciously. In extreme cases, shielding the research subject with a Faraday cage may be required.

The noise generated internal to the preamplifier is a significant concern because it represents the major component of the total amplifier noise.[12] Amplifier noise can be reduced to very low levels by the use of battery operated low power preamplifiers and postamplifiers. Amplifier noise usually is specified in microvolts RMS, referred to the input (RTI). The ISEK recommends amplifier noise be less than 5 μVRMS measured with a source resistance of 100 k Ω and a bandwidth from 0.1 to 1000 Hz.[14]

Finally, the amplifier input bias current should be specified. This variable is important because it determines the minimum signal that can be amplified. Low input bias currents are desirable to minimize the effect of changes in electrode source impedance that may occur as a result of electrode movement. Applying Ohm's law, the amplitude of the movement artifact is equal to the change in the source impedance multiplied by the input bias current. The ISEK recommends input bias current be less than 50 nA for direct coupled amplifiers.[14]

A summary of recommended minimum specifications for surface EMG amplifiers may be found in Table 4-2. These specifications may serve as a general guideline for the selection of equipment appropriate for use in surface EMG.

Onsite Electrode-Preamplifiers

The development of small onsite surface electrode-preamplifiers, or **active** surface electrodes, has been the result of the natural evolution of equipment design as a response to the inconvenience and unreliability of conventional surface electrodes.

The improved performance of active surface electrodes is due to the inherent advantages of moving the preamplifier as close as possible to the signal source. This advantage, coupled with improvements in direct current amplifier performance, has resulted in improved signal-to-noise ratios and the near elimination of problematic motion artifacts. An example of a typical surface electrode of this type was presented in Chapter 3. The demand for convenient electrode application has resulted in active electrode designs with very high input impedance (10^{12} Ω) that require no electrode paste or skin preparation.

TABLE 4-2
Recommended Minimum Specifications for Surface EMG Amplifier

Variables	Recommended Minimal Specifications
Input impedance	$> 10^{10}\ \Omega$ at DC[a,b] $> 10^{8}\ \Omega$ at 100 Hz[a,b]
Amplifier gain	200—100,000 ±10% in discrete increments
Gain nonlinearity	$\leq \pm 2.5\%$
Gain stability	Combined short term (1 day) and long term (1 year) gain variations < 5%/year
Common mode rejection ratio (CMRR)	> 90 dB measured at 60 Hz with zero source resistance[a]
Frequency response	1—3000 Hz measured at —3 dB points[a]
Input bias current	< 50nA (50×10^{-9} A)[a]
Isolation	≤ μA (10×10^{-6} A) leakage current measured between patient leads and ground (Underwriters Laboratories, 1985)
Noise	< 5 μV RMS measured with a 100 k Ω source resistance[a]

[a] Indicates minimum specifications recommended by the International Society of Electrophysiological Kinesiology.[14]

[b] The ISEK specification for input impedance does not differentiate between the requirements for surface versus indwelling electrodes, electrode material, the length of electrode leads, and other factors that may effect the magnitude of input impedance required to maintain the ratio of the input impedance to the lumped electrode source impedance at a minimum of 100:1. The ISEK recommendation is broad enough to apply to all these varied conditions. A lesser input impedance specification may be adequate within a limited set of conditions.

ELECTROMYOGRAPHIC SIGNAL PROCESSING

The processing of the EMG signal to obtain information relevant to an experimental question has taken many forms. To this point in our discussion, we have emphasized the need to preserve the information content of the detected EMG without preference to a specific measurement goal. A low noise, high input impedance linear amplifier with a bandwidth of from 1 to 3000 Hz and adequate gain to amplify the peak EMG to a 1 V output level will ensure signal fidelity. This performance is recommended to allow the raw unadulterated EMG to be monitored and, in some cases, stored. Monitoring the raw data is necessary to ensure the quality of the signal before or during processing so that the processing does not eliminate the recognition of interference and artifacts.

Anyone who has observed a several second record of EMG activity from a complementary muscle pair, such as the forearm flexors and extensors, during a working task will be struck by the phasic nature of the activity. The flexors will be very active during one phase of the cycle, while the extensors will be active during another phase. During such a brief period of visual examination of such a record by the electromyographer, the brain makes comparisons between the signal information and the general character of the movement and makes decisions on what is valuable information. The rapid random fluctuations in the signal are ignored as being due to the random summation and subtraction of the many muscle fiber action potentials detected. Instead, attention is paid to the boundary or envelope of the EMG signal. This signal processing is context specific and intuitive and has a quantitative basis that the majority of signal processing methods seek to mimic and even exploit. A notable exception is the frequency analysis technique used in detection of muscle fatigue, the technique for which will be discussed separately.

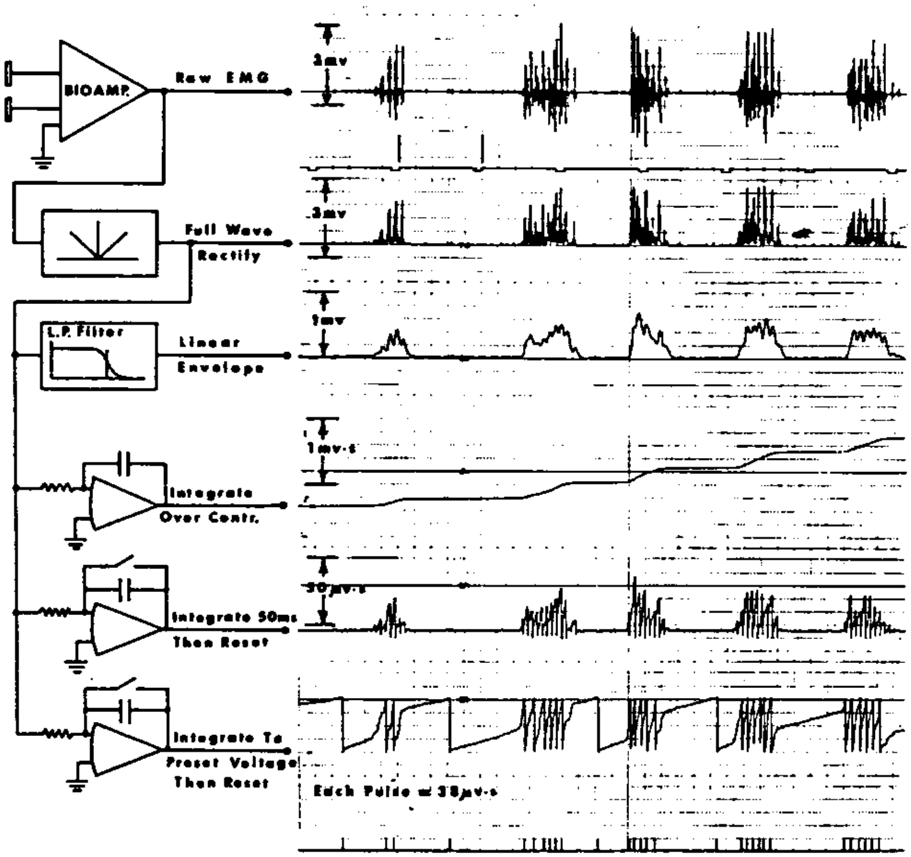

FIGURE 4-5

Schematic of several common EMG processing systems and the results of simultaneously processing of EMG through these systems.

Reprinted with permission from Winter DA: Biomechanics of Human Movement. New York, NY, John Wiley & Sons Inc, 1979, Figure 7.10, p 140.

EMG Demodulation

Concepts

The terms modulation and demodulation are familiar in the communications industry. They refer to methods of modulating low frequency information on high frequency carriers to simplify broadcast transmission over long distances. Once the modulated signal reaches its destination, the original low frequency information is retrieved by demodulation. All radio and television signals undergo this process. In a similar way, the detected EMG has been modulated by the command of the alphamotoneuron pool.[15] An increase in the command is represented by an increase in the level of net postsynaptic depolarizations of all the neural inputs to a muscle. This in turn causes the rate of motor unit firings to be frequency modulated by the neural command. Finally, the summation of the frequency modulated motor-unit action potentials produces an amplitude modulated envelope representative of the recruitment and firing rates of the original neural command. Demodulation, in this context, refers to processing techniques that recover the information associated with the neural command and discard everything else. Figure 4-5 illustrates several common EMG processing systems and the results of simultaneous demodulation of the raw EMG through these systems.

Demodulation Techniques

Rectification

The raw EMG detected by surface electrodes and amplified by a linear differential amplifier is a bipolar signal whose random fluctuations, if summed over a significantly long time period, would produce a zero result. Rectification is one technique frequently used in EMG-processor designs to translate the raw signal to a single polarity. This translation may be accomplished by either eliminating one polarity of the signal (half-wave rectification) or by inverting one polarity (full-wave rectification). Zero offset full-wave rectification is the preferred method because in this case all the signal energy is preserved. The effects of full-wave rectification is illustrated in Figure 4-5.

Linear Envelope Detector

The linear envelope detector is one of the least complex and most often used circuits for approximating the modulating neural control. The circuit consists of a zero offset full-wave rectifier followed by a low-pass filter (Figure 4-5). The cutoff frequency of the filter is selected to allow the capacitor voltage to track the envelope with the degree of smoothness desired. The effect of the low.pass filter response is to average the variation that occurs in the input signal. Hence, it is associated closely with the mathematical average or mean of the rectified EMG signal. The primary distinction is that the output of the linear envelope detector represents a **moving average** of EMG activity. An undesirable side effect of the low-pass filter is the phase lag it causes in the envelope response. This lag may introduce significant errors in the measurement of temporally related variables.

The cutoff frequency of the filter is selected by evaluating the kinetics-kinematics of the experiment in the context of the measurement goal. If an investigator, for example, wishes to use EMG as an indirect measure of the force produced during a 1-second constant force isometric contraction, a cutoff frequency of 1 Hz would ensure adequate response while offering maximum smoothing. On the other hand, the EMG associated with dynamic movements, such as quick movements of an arm during a working motion, would require a cutoff of the same frequency order as the movement itself. As frequencies of human movement generally do not lie above 6 Hz, no frequency thought to represent muscle control should necessarily lie above 6 Hz.[16]

Contemporary filter designs feature transfer characteristics that improve the rate of attenuation above the cutoff frequency. The rate of attenuation is related to the **order** or the number of **poles** of the filter design. All filters roll off at 6 dB/octave (20 dB/decade) for each pole in the network. It is important that investigators report the filter design (eg, Butterworth, Bessel), the order of the filter, and the cutoff frequency used when communicating research findings. The unit for the moving average is millivolt (mV) or microvolt (μV).

Integration

Integration refers to the mathematical operation of computing the area under the curve. Because the integral of the raw EMG is zero, it is necessary to full-wave rectify the raw signal to obtain the absolute value. This operation is expressed as follows:

$$I\{|EMG(t)|\} = \int_{0}^{t} |EMG(t)|dt \qquad (3)$$

As is evident from the formula, the integral will increase continuously as a function of time. In practical integrator designs, the time period must be limited because of the limited dynamic range of the integrator circuit. Typically, this is accomplished by integrating over fixed time intervals. In such cases, the operation is expressed as follows:

$$I\{|EMG(t)|\} = \int_{t}^{t+T} |EMG(t)|dt \qquad (4)$$

where T is the fixed time interval. Figure 4-5 illustrates the continuous integration as well as time and voltage reset integration. The EMG integral is a two dimensional quantity whose unit is mV• s or μV• s.

Root-Mean-Square Processing

The root-mean-square (RMS) is a fundamental measure of the magnitude of an AG signal. Root-mean-square processing is a method that allows consistent, valid, and accurate measurements of noisy, nonperiodic, nonsinusoidal signals. It has been widely used in engineering applications to measure a host of phenomena from vibration and shock to thermal noise.

Mathematically, the RMS value of an EMG voltage is defined as follows:

$$RMS\{EMG(t)\} = (\frac{1}{T} \int_{t}^{t+T} EMG^2(t)dt)^{½} \qquad (5)$$

Unlike previous detection methods, the RMS processor does not require full-wave rectification, because the time varying EMG signal is squared. This nonlinear operation is the basis of the square-law amplitude demodulator.[17] Root-mean-square processing has enjoyed increasing popularity as investigators have become more aware of its benefits. DeLuca and Van Dyk have demonstrated that the RMS value contains more relevant information than the mean rectified or integrated EMG.[2] In particular, the RMS is not affected by the cancellation caused by the superposition of motor unit action potential trains.

Low cost analog integrated circuits are commercially available for performing the RMS computation. These designs invariably incorporate a low-pass filter to compute the average or mean. As with the linear envelope detector, a trade off must be made between the response of the circuit and the allowable DC error. Longer time constants create less DC error but longer settling times. Settling times may be longer for decreasing signals than for increasing signals, depending on the particular design. This characteristic may cause timing errors if too long a time constant is employed. The unit of the RMS EMG is mV or μV.

Demodulation Applications

Conceptually, demodulation may be viewed as an information filtering process. The raw EMG contains information about a great number of factors, such as the contribution of a single muscle fiber, that when considered individually play only a minor role in the resultant muscle contraction. The demodulation process allows us to filter out the information specific to the individual signal contributors and to maintain the information concerning the general behavior of the individual contributors taken together. Information from demodulated EMG, therefore, may only be used to answer research questions concerned with the general neural control of muscle.

Demodulation signal processing techniques are used commonly to obtain temporal and EMG-force information. All the techniques discussed may be used to obtain temporal information, with the integrator being least suitable, as a result of the nature of the measurement unit. Caution must be exercised, however, in the selection of an appropriate cutoff frequency or integration interval. It is recommended that the processed signal be compared with the raw EMG using either an oscilloscope or a recorder with a sufficiently high frequency response (see section on monitors and recorders later in this chapter). In this manner, time delays in the processed waveform can be identified. The identification of specific temporal events requires that the information content of the processed signal be further reduced. This may be accomplished in a number of ways. The classic method is first to output the processed data to a strip chart recorder, then to measure the distance between significant temporal events and divide the distance by the chart speed. This method can be very time consuming and is subject to reading error. Automated and semiautomated procedures are becoming more common, largely because of the low cost of powerful microcomputers and the availability of appropriate software. The primary disadvantage of automated procedures is that they are often unable to distinguish noise artifacts from genuine signals. As a result, commercial software packages often require user visual recognition of events and positioning of a time cursor.

The sophistication required to identify significant temporal events correctly has limited the application of hardware based data reduction methods. Amplitude discriminators and threshold detectors may be of considerable assistance in identifying the presence or absence of muscle activity. Like other automated methods, however, they are susceptible to noise artifacts.

Besides temporal measurements, the other major application area for demodulation processing techniques involves the quantification of the amplitude of the EMG envelope for the purpose of predicting muscle force or joint torque. The data reduction options applicable to this category of EMG measurement are similar to those discussed in connection with temporal measurements. In this context, however, the process of reducing the information content is far more, laborious because of the magnitude of information that must be necessarily considered. Computers are invaluable in this regard in that they have the capability of time-sampling signals from multiple variables, storing the information in ordered arrays, and performing mathematical and logical operations.

Frequency Domain Processing

Transformation of Random Processes

Often, the solution to a complex problem becomes easier to comprehend if viewed from an entirely different perspective. Frequency domain processing is used to shift the electromyographer's reference to the information content of the EMG signal intentionally from the time domain to the frequency domain. The value of the technique is in simplifying the identification and quantification of EMG information that manifests itself as changes in EMG frequency content. A common use of this technique in EMG is to identify EMG frequency spectrum shifts believed to be related to localized muscle fatigue (see Chapters 5 through 7).

As discussed previously, the Fourier transform is the mathematical technique by which the time-to-frequency-domain transformation is performed. The technique is general and applicable to many diverse areas. Of particular relevance to the electromyographer is the use of the Fourier transform in the context of random processes. Electromyographic signals are neither periodic nor deterministic.[18] Indeed, they do not repeat with a definite time interval, and a single mathematical expression cannot specify a detected EMG signal for all time. An EMG interference pattern, therefore, must be treated as a random or stochastic process with an associated cumulative probability distribution.

The power spectral density is the function commonly used for frequency domain analysis of EMG. It is defined as the Fourier transform of the autocorrelation function.[19] The autocorrelation function may be computed from the time average of a sufficiently long finite length of data if one assumes the random process to be ergodic.[20] For a random process to be ergodic it must 1) have a normal or Gaussian probability distribution, 2) be stationary over the time period of the average, and 3) have an average value of zero. The formula for computing the autocorrelation function R(τ) from the time average of the EMG is as follows:

$$R(\tau) = \lim_{T\to\infty} \frac{1}{t} \int_{-T/2}^{T/2} \mathrm{EMG}(t, \varepsilon)\ \mathrm{EMG}(t+\tau, \varepsilon)\,dt \qquad (6)$$

where ε represents the random outcome of an experimental event, t the time course of the random event, τ the time difference, and T the period of the time average. A close examination of the equation will reveal that the autocorrelation in this context is simply the mean of the product of the same signal displaced by τ seconds and computed for all time displacements.

The Fourier transform G(f) for any nonperiodic signal s(t) is given by the following:

$$G(f) = \int_{-\infty}^{\infty} s(t)e^{-j2\pi ft}\,dt \qquad (7)$$

The power spectral density P(f), defined as the Fourier transform of the autocorrelation function becomes as follows:

$$P(f) = \int_{-\infty}^{0} R(\tau)e^{-j2\pi ft}\,dt \qquad (8)$$

As P(f) is an even function, the integrals are real numbers and the equation can be written as follows:

$$P(f) = \int_{-\infty}^{\infty} R(\tau) \cos 2\pi f\gamma d\tau \qquad (9)$$

An integration of P(f) over all frequencies yields the total power, hence the term power spectrum.

Fast Fourier Transform

As implied by name, the fast Fourier transform (FFT) is an efficient method of computing a discrete Fourier transform. The discrete Fourier transform must be used in frequency transformations of sampled functions, such as the type created by digital computer sampling at discrete instants. The computer is an indispensable aid to that type of computation because of the number of mathematical operations necessary for the calculation of the transform. The treatment of this topic follows the logical development of the discrete Fourier transform from the continuous Fourier transform as presented by Brigham.[21,22]

Waveform Sampling

When a signal is sampled at discrete instants, the effect is to multiply the signal by a unit sampling pulse train. This is illustrated graphically in Figure 4-6 where the function h(t) is sampled at discrete sampling intervals defined by T. The resultant sampled waveform (Figure 4-6e), thus, is an infinite sequence of equidistant impulses, the amplitude of each corresponding with the value of h(t) at the time of occurrence of the sampling impulse. The Fourier transforms of h(t) and Δ(t) are shown in Figure 4-6c and d, respectively. The symbol □ is used to designate a Fourier transformation. The frequency convolution theorem establishes multiplication in the time domain as equivalent to convolution in the frequency domain. This is demonstrated graphically in Figure 4-6 by noting that the function H(f)*Δ(f) (Figure 4-6f) is the Fourier transform of the sampled waveform h(t) Δ(t) (Figure 4-6e) and may be formed by the convolution of the Fourier transforms of the original functions shown in Figure 4-6c and d. What is of particular significance in the application of the Fourier transform to time sampled functions is the relationship between the continuous Fourier transform, shown in Figure 4-6c, of the original continuous function h(t) and the continuous Fourier transform, shown in Figure 4-6f, of the sampled function h(t) Δ(t). The waveforms are identical with the exception that the continuous Fourier transform of the sampled waveform is periodic, with a period equal to the sampling interval T.

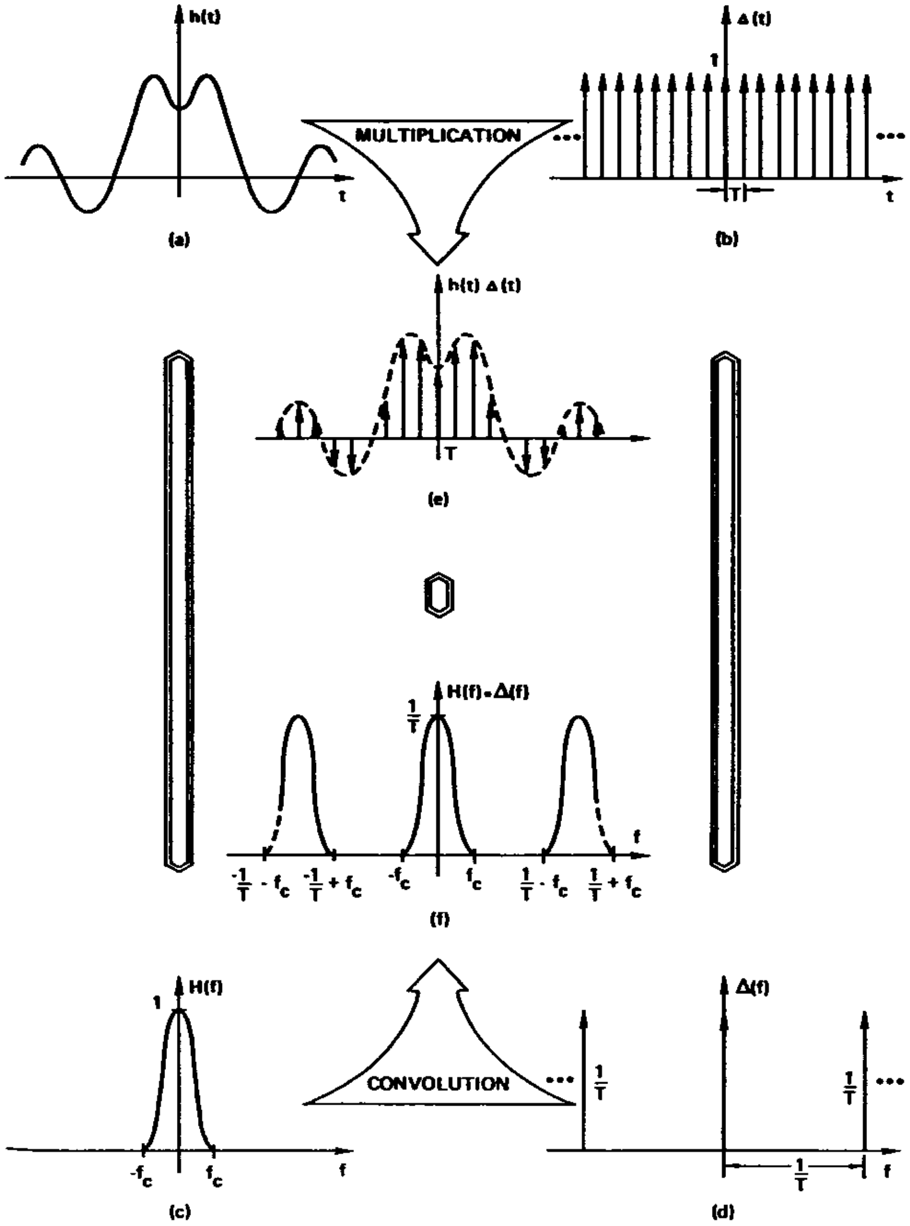

FIGURE 4-6

Graphical frequency convolution theorem development of the Fourier transform of a sampled waveform.

Reprinted with permission from Brigham EO: The Fast Fourier Transform. Englewood Cliffs, NJ, Prentice-Hall Inc, 1974, Figure 5-3, p 81.

Aliasing

If the sampling interval is too large, an overlapping of the periods of the continuous Fourier transform of the sampled function h(t) Δ(t) will occur as shown in Figure 4-7f. This distortion is known as aliasing. Referring to the sampling function Δ t, note that as the sample interval T is increased (Figure 4-6b and Figure 4-7b), the impulses of its transform pair Δ f become more closely spaced (Figure 4-6d and Figure 4-7d). It is the decreased spacing of the frequency impulses, which when convoluted with the frequency function H(f) result in the alaised waveform of Figure 4-7f. As the name alias implies, the waveform of Figure 4-7f is not representative of the frequency information needed to characterize the original signal h(t). Indeed. the waveform h(t) cannot be reconstructed from the aliased waveform.

The condition necessary to prevent overlapping of the Fourier transform of the sampled waveform is when the sampling frequency (1/T) is at least twice the frequency of the highest frequency component (fc) of the Fourier transform of the continuous function h(t). The frequency 1/T = 2 fc, known as the Nyquist sampling rate, is the minimum frequency at which no overlapping will occur. This condition is represented in Figure 4-8.

A difficulty arises in selecting an appropriate sampling frequency for EMG because it is impossible to know precisely the highest frequency component in the detected EMG. This is because the EMG frequency spectrum is influenced by several factors, the most obvious being the interelectrode spacing.

The usual method used to select the sampling frequency for fast Fourier analysis is first to make a guess of the highest frequency component in the signal, based on electrode type and instrumentation specifications, and then to select a sampling frequency three or four times greater than that frequency.[18] Confusion often exists concerning the application of the Nyquist sampling rate to digital sampling in general. Although the Nyquist rate does define the minimum sampling rate to recover the information content of a signal, electromyographers who rely on visual recognition or identification of significant signal attributes will find the Nyquist rate to be inadequate for recovering the same information. This problem may be appreciated by considering the difficulty of reconstructing a sine wave from two visual samples. Sampling at frequencies 10 times the highest frequency of interest in the signal is suggested as a conservative guideline when the methods of data recovery do not incorporate spectral analysis.

Discrete Fourier Transform

The discrete Fourier transform (DFT) is a method that is compatible with digital computers and that approximates the results of a continuous transform. To allow for computer calculation of the Fourier transform, the sampled time function and its Fourier transform pair must be represented by a finite number of discrete values.

To appreciate how the discrete Fourier transform differs from the continuous transform, consider the graphical derivation of Figure 4-9. The function h(t) is multiplied by the sampling function Figure 4-9b to produce the sampled function, and its Fourier transform pair is illustrated in Figure 4-9c. The aliasing depicted in the sampled function's transform pair (Figure 4-9c) is due to a failure to satisfy the Nyquist sampling rate given the bandwidth of the original function h(t). The Fourier transform pair of Figure 4-9c is not appropriate for digital computer calculation because an infinite number of samples of h(t) are required. It is necessary, therefore, to truncate the sampled function with the rectangular function as illustrated in Figure 4-9d. The effect of truncation is to convolve the frequency transform of Figure 4-9c with the Fourier transform of the truncation function illustrated in Figure 4-9d. This has the negative effect of causing a ripple in the frequency transform of Figure 4-9e. This error may be reduced by increasing the length of the truncation function. It is desirable, therefore, to select as long a truncation function as possible.

The transform pair of Figure 4-9e must be modified further to make it possible to represent the frequency transform with discrete values. This may be accomplished by sampling the frequency transform of Figure 4-9e with the frequency sampling function of Figure 4-9f using a frequency sampling interval of 1/T. The resulting discrete transform pair of Figure 4-9g, approximates the original continuous transform of Figure 4-9a with N discrete samples. Basmajian et al states, "if the original time function is real (as in the case of an autocorrelation) then the real part of the DFT is symmetric about the so-called folding frequency, which is by definition equal to half the sampling frequency."[18]

Modulo Two Requirement

A constraint of the FFT algorithm is the requirement that the number of samples, N, be an integral power of two. For periodic waveforms, it is difficult or, in some cases, impossible to sample the signal at three or four times the highest frequency component in the signal and then to truncate the sampled function in such a way as to represent a single period of the function, with an integral power of two samples. In these cases, it is customary to complete the sampling interval with a number of zero valued samples.

For random events associated with EMG activity, the EMG waveform is nonperiodic, and the modulo two

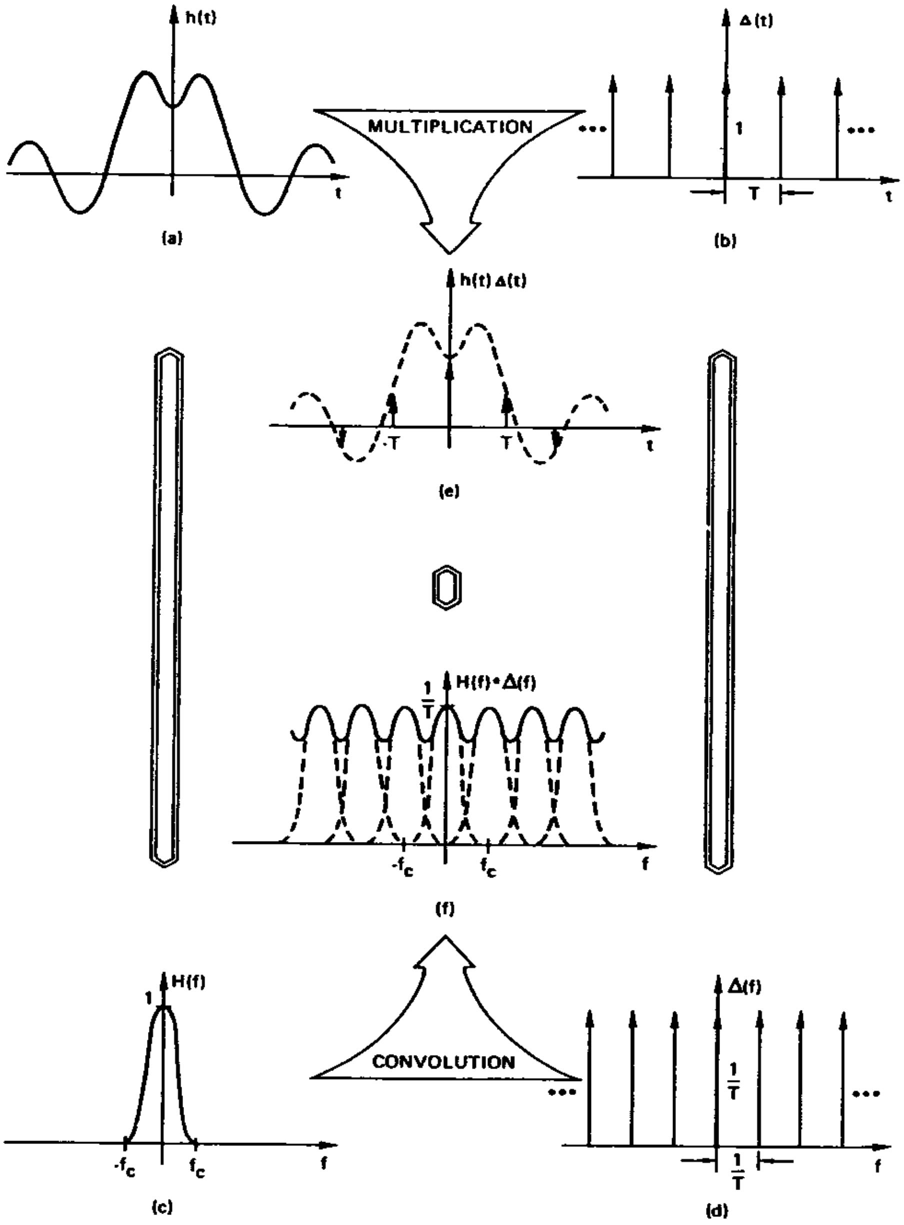

FIGURE 4-7
Aliased transform of a waveform sampled at an insufficient rate.

Reprinted with permission from Brigham EO: The Fast Fourier Transform. Englewood Cliffs, NJ, Prentice-Hall Inc, 1974, Figure 5-4, p 82.

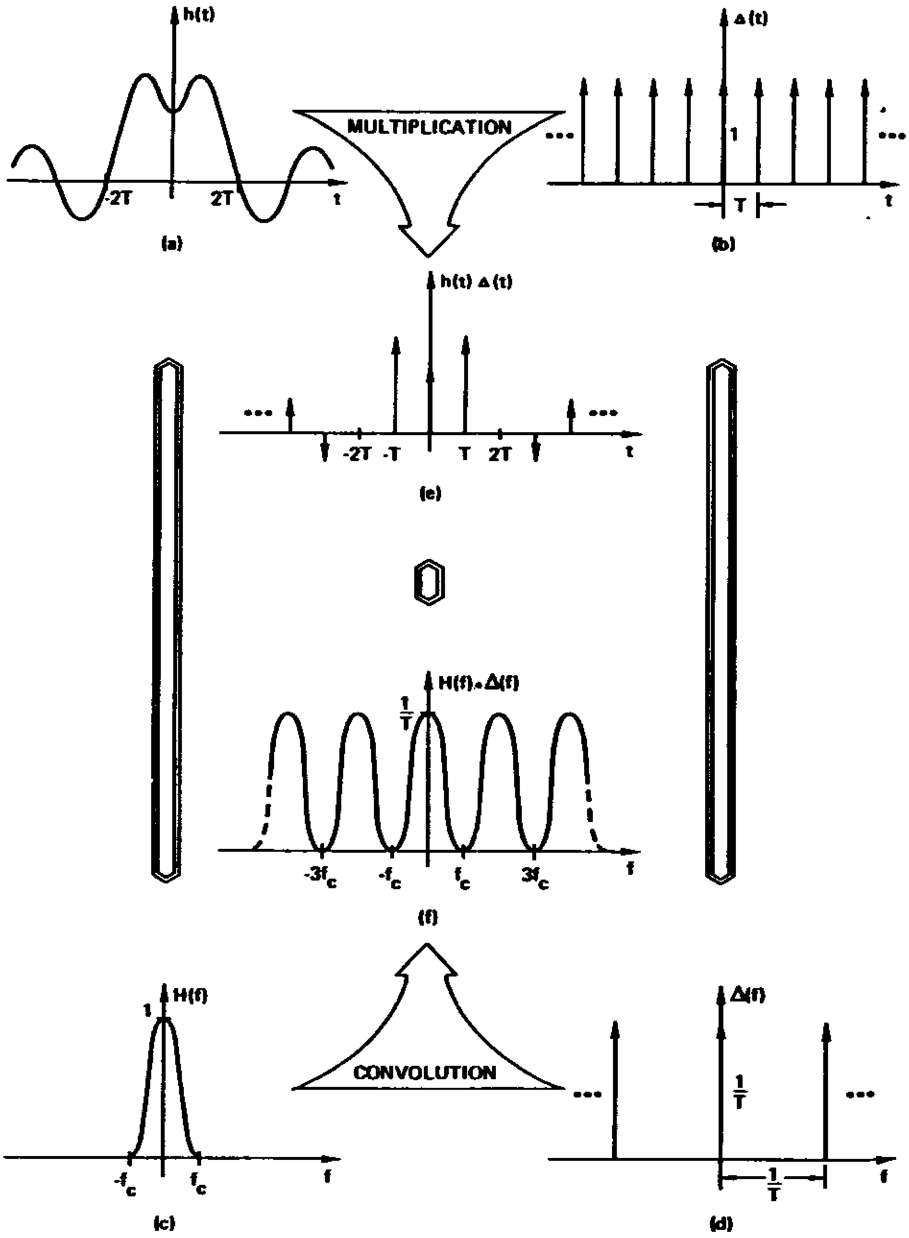

FIGURE 4-8
Fourier transform of a waveform sampled at the Nyquist sampling rate.

Reprinted with permission from Brigham EO: The Fast Fourier Transform. Englewood Cliffs, NJ, Prentice-Hall Inc, 1974, Figure 5-5, p 84.

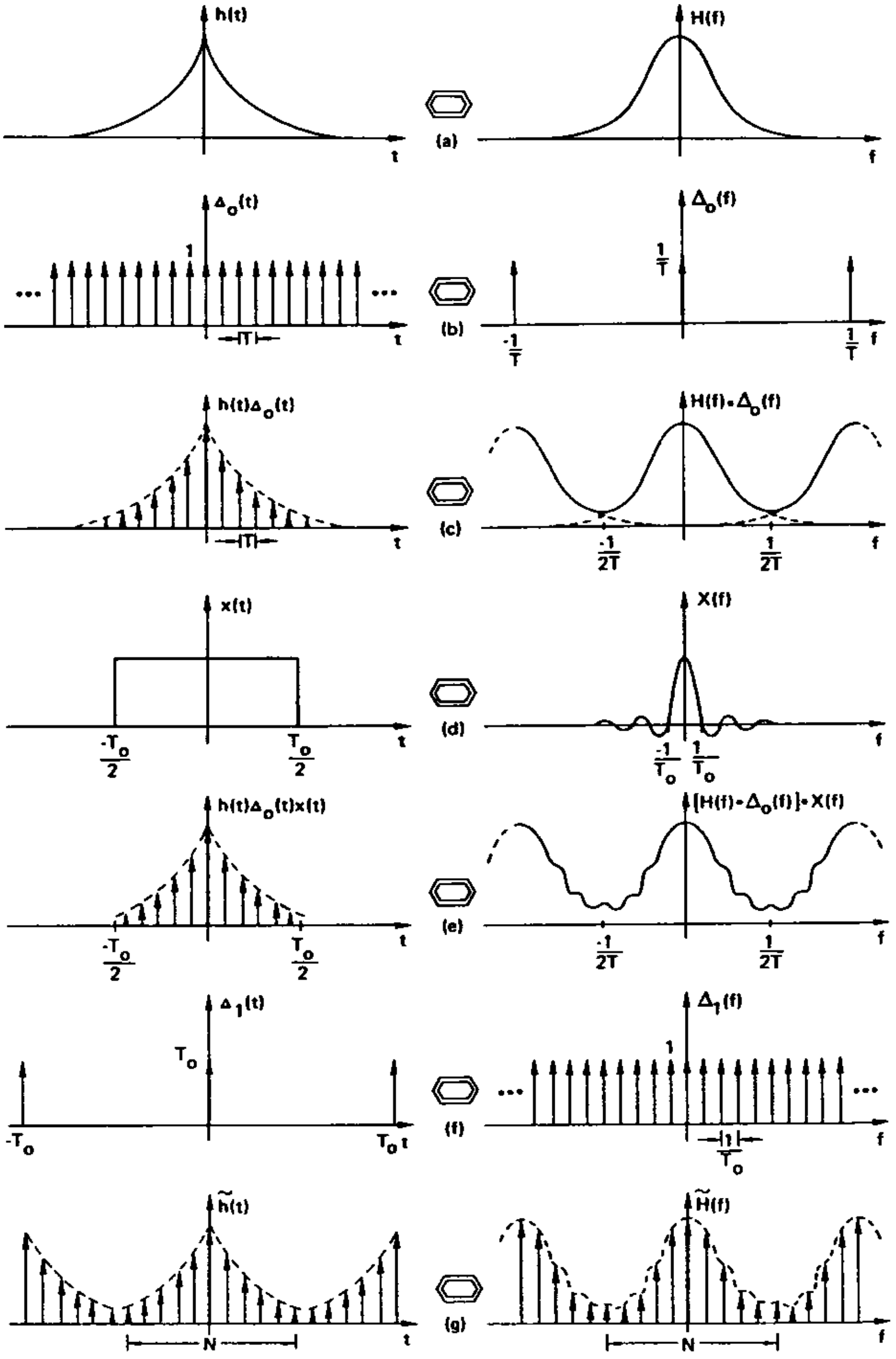

FIGURE 4-9
Graphical development of the discrete Fourier transform.

Reprinted with permission from Brigham EO: The Fast Fourier Transform. Englewood Cliffs, NJ, Prentice-Hall Inc, 1974, Figure 6-1, p 92.

requirement is less difficult to satisfy. Caution must be exercised, however, in the choice of the truncation interval because of the requirement that the random process be stationary.[18]

Windowing Functions

The time domain truncation inherent in the discrete Fourier transform has the potential to create sharp discontinuities in the sampled function corresponding to the beginning and end of the truncation function. These sharp changes in the time domain result in additional frequency components, termed leakage, in the frequency domain.

Referring again to Figure 4-9, recall that the ripple generated in the Fourier transform of the truncated sampled function (Figure 4-9e) was created by the convolution of the frequency transform of the sampled function (Figure 4-9c) and the characteristic sin(f)/f function of the rectangular truncation function (Figure 4-9d). It is the side-lobe characteristic of the sin(f)/f function that results in the ripple, or leakage. To reduce the negative effects of leakage, it is desirable to use truncation function that has reduced side-lobe characteristics in place of the rectangular truncation function.

The FFT weighting or windowing functions illustrated in Figure 4-10 are compared with the rectangular function in both the time and the frequency domains. As shown, all the windowing functions have reduced side lobes as compared with the rectangular function. Unfortunately, all the windowing functions also have a broader main lobe (Figure 4-10b). This has the undesirable effect of smearing the results of the FFT, which results in decreased frequency resolution.

The equation for the windowing functions of Figure 4-10 are given in Table 4-3, along with the highest side-lobe levels, −3 dB bandwidth, and rolloff rates. The Hanning or similar Hamming window are widely used as truncation functions in the application of the FFT to myoelectric signals.[7]

RECORDERS

The purpose of a recorder is to provide a permanent time record of the variations in the input signal that can be reviewed later to obtain data for analysis. The rational for selecting a recorder for an EMG recording application will depend on both the faithful reproduction of the EMG waveform and the end goal of the information gathering process. As with other parts of the instrumentation system, the recorder must possess the appropriate amplitude and phase linearity, bandwidth, and noise level, necessary to preserve the desired information contained in the signal. Beyond these essential characteristics, there are many other practical considerations in selecting a recorder. Among these are the cost of the recorder, the cost of the recording media, the storage requirements of the recording media, and the ease and accuracy with which data may be extracted from the record.

Graphic Recorders

Graphic recorders are distinguished by their ability to provide a permanent graphic recording of the time variations of the EMG waveform. The most common type of graphic recorder is the pen-and-ink recorder in which an ink delivering stylus is mechanically positioned to produce an ink tracing on a moving paper surface. A key design factor associated with the pen-and-ink recorder is the method used to position the stylus mechanically, because the response of the stylus limits the bandwidth of the recorder. Pen-and-ink recorders using a galvanometer positioning mechanism rarely have a full scale bandwidth greater than 60 Hz. This clearly is inadequate for recording raw EMG, but may be used for recording demodulated waveforms.

Several ingenious recorder designs have improved on the bandwidth limitation of the basic pen-and-ink galvanometric recorder by eliminating the stylus and replacing it with other writing methods. The light beam oscillograph incorporates a tiny mirror attached to the galvanometer mechanism to direct a light beam onto light sensitive recording paper. The low mass of the mirror improves the frequency response of this recorder design to 1000 Hz and above, suitable for recording raw EMG signals.

Two new graphic recorder designs incorporate computer processing and control with unique writing methods. One design incorporates a direct writing thermal array to produce permanent recordings on heat sensitive paper. Another design uses an electrostatic writing system to apply toner to the paper. Both of these designs have the advantage of being programmable with no overshoot or limits on transient response resulting from inertia. As a result, the recorder may be programmed to adjust the paper width allotted to each channel, greatly improving the amplitude resolution over other designs. Although the frequency response of both recorder types is adequate to represent the amplitude of raw surface EMG accurately, their usefulness in timing studies is limited by their writing speeds. Selecting one manufacturer's specification for each recorder type as representative, the maximum chart speed was 10 cm/s for the direct writing thermal array recorder and 25 cm/s for the electrostatic recorder. Given the usual circumstances for recording EMG in ergonomic situations, these paper speeds should be adequate if this recording mode be desired.

TABLE 4-3

Data Weighting Functions ($T_o = NT$)[a]

Weighting Function Nomenclature	Time Domain	Frequency Domain	Highest Side-Lobe Level (db)	3-dB Bandwidth	Asymptotic Rolloff (dB/Octave)
Rectangular	$W_R(t) = 1 \quad \lvert t\rvert \le \frac{T_0}{2}$ $= 0 \quad \lvert t\rvert < \frac{T_0}{2}$	$W_R(f) = \frac{T_0 \sin(\pi f T_0)}{\pi f T_0}$	- 13	$\frac{0.85}{T_0}$	6
Bartlett (triangle)	$W_B(t) = \left[1 - \frac{2\lvert t\rvert}{T_0}\right] \quad \lvert t\rvert < \frac{T_0}{2}$ $\lvert t\rvert > \frac{T_0}{2}$	$W_B f = \frac{T_0}{2}\left[\frac{\sin\left(\frac{\pi}{2} f T_0\right)}{\frac{\pi}{2} f T_0}\right]$	- 26	$\frac{1.25}{T_0}$	12
Hanning (cosine)	$W_H(t) = \cos^2\left(\frac{\pi t}{T_0}\right)$ $= \frac{1}{2}\left[1 + \cos\left(\frac{2\pi t}{T_0}\right)\right] \quad \lvert t\rvert \le \frac{T_0}{2}$ $= 0 \quad \lvert t\rvert > \frac{T_0}{2}$	$W_H(f) = \frac{T_0}{2} \frac{\sin(\pi f T_0)}{\pi f T_0[1 - (f T_0)^2]}$	- 32	$\frac{1.4}{T_0}$18	
Parzen	$W_P(t) = 1 - 24\left(\frac{t}{T_0}\right)^2 + 48\left\lvert\frac{t}{T_0}\right\rvert^3 \quad \lvert t\rvert < \frac{T_0}{4}$ $= 2\left[1 - \frac{2\lvert t\rvert}{T_0}\right]^3 \quad \frac{T_0}{4} < \lvert t\rvert < \frac{T_0}{2}$ $= 0 \quad \lvert t\rvert \ge \frac{T_0}{2}$	$W_P(f) = \frac{3T_0}{8}\left[\frac{\sin(\pi f T_0/4)}{\pi f T_0/4}\right]^4$	- 52	$\frac{1.82}{T_0}$	24

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[a] Reprinted with permission from Brigham EO: The Fast Fourier Transform and Its Applications. Englewood Cliffs, NJ, Prentice Hall Inc, 1988, Tab. 9.1, p 182.

Machine-Interpretable Recorders

Central to the function of any recorder is the ability to store information. In the case of a graphic recorder, the information is stored in the graphic record itself. Machine-interpretable records store information in a form that cannot be read or interpreted without a machine interface.

FM Magnetic Tape Recorders

The appeal of the FM tape recorder as a storage device is its ability to reconstruct the EMG waveform in its original analog form at the convenience of the investigator. During a recording session, the electromyographer is free to focus attention on the data collection aspects of an experiment, even voice annotating the record during significant events. Subsequently, the investigator may review individual channels and perform alternative data reduction and analysis methods using the original analog signal. The long-term storage aspect of the FM recorder allows data to be reanalyzed using methods that were unavailable or unappreciated at the time of the data collection. The FM recorders are preferred over other direct analog recording designs because of their superior linearity, harmonic distortion, noise level, and DC response. The DC response is necessary for recording the output of transducer types normally associated with EMG, such as force, joint position, and acceleration. The bandwidth of an FM tape recorder is proportional to the tape speed. It is necessary, therefore, to select a recording speed that provides a bandwidth adequate for the signal being recorded.

The ability to record data in real time at a fast tape speed and play back at a slower tape speed has the effect of slowing time. This effect may be used to extend the bandwidth of an ordinary pen-and-ink recorder artificially and allow the recording of raw EMG signals. Thus, recording at a tape speed of 15 ips and replaying at 15/32 ips can produce a bandwidth expansion factor of 32. When multiplied by the typical pen-and-ink bandwidth of 60 Hz, the effective bandwidth is extended to 1920 Hz.

The primary drawback to the use of an FM recorder concerns the reduction in the signal-to-noise ratio that is likely to occur. The recorder signal-to-noise specification defines the upper limit of this ratio for a signal covering the full dynamic range of the input. The EMG signals are characterized by a large dynamic range spanning the signal amplitude from those generated by a few motor units to those generated by a maximal contraction. Consequently, for a 0.1 V signal recorded on a recorder with an input dynamic range of ±1.0 V and a signal-to-noise ratio of 100:1 (40 dB), the actual signal-to-noise ratio is 5:1 (14 dB) or 20% noise. This level of noise may well be intolerable.

Digital Recorders

The widespread use of digital computers to process experimental data has created a need for recorders that can store large quantities of data and can provide the data in a digital format suitable for direct computer input. The digital magnetic tape recorder and the digital magnetic disk are the two most popular digital recording technologies. In both types, a numerical value is represented by a formatted digital code. The codes used have been standardized to allow data to be interchanged between different computer types and software applications. Unlike FM tape recorders, the density of the information placed on the digital tape or disk media is independent of the frequency content of the information. All blocks of the coded data are formatted in the same way. Consequently, signals with high frequency components require proportionally more storage. For wide-band EMG signals, this will require thousands of stored values for each second of recorded data. Fortunately, the capacity of digital storage technologies are increasing rapidly at the same time the price per storage unit is dropping, making digital storage of EMG data attractive in many applications.

In comparing analog and digital recording methods, it is important to realize that the digital recorder does not digitize the EMG data itself, but rather it relies on another computer-controlled process termed analog-to-digital conversion. The fidelity of digitally recorded data as representative of an analog EMG waveform is dependent primarily on the performance of the analog-to-digital converter. For EMG signals that eventually will be digitized and processed using computer methods, digital storage is advantageous because this technique side-steps the noise and distortion problems of FM recorders.

ANALOG-TO-DIGITAL CONVERSION

Clearly, from the foregoing discussion, analysis of EMG measurements very often requires digitization of the signal and subsequent numerical computations. This is true particularly when relating EMG signals to other simultaneously measured variables such as force, position, and angle and when addressing issues of muscular fatigue that require processing in the frequency domain. The term analog-to-digital convertor is used to describe any component or device which changes a continuously varying signal, such as EMG, into a discrete number representing the amplitude of that signal at some particular instant in time.

Theory of Operation

Theoretically, an analog signal like EMG is continuously variable over its entire range. In practice, there is a finite resolution to the numerical value that is assigned

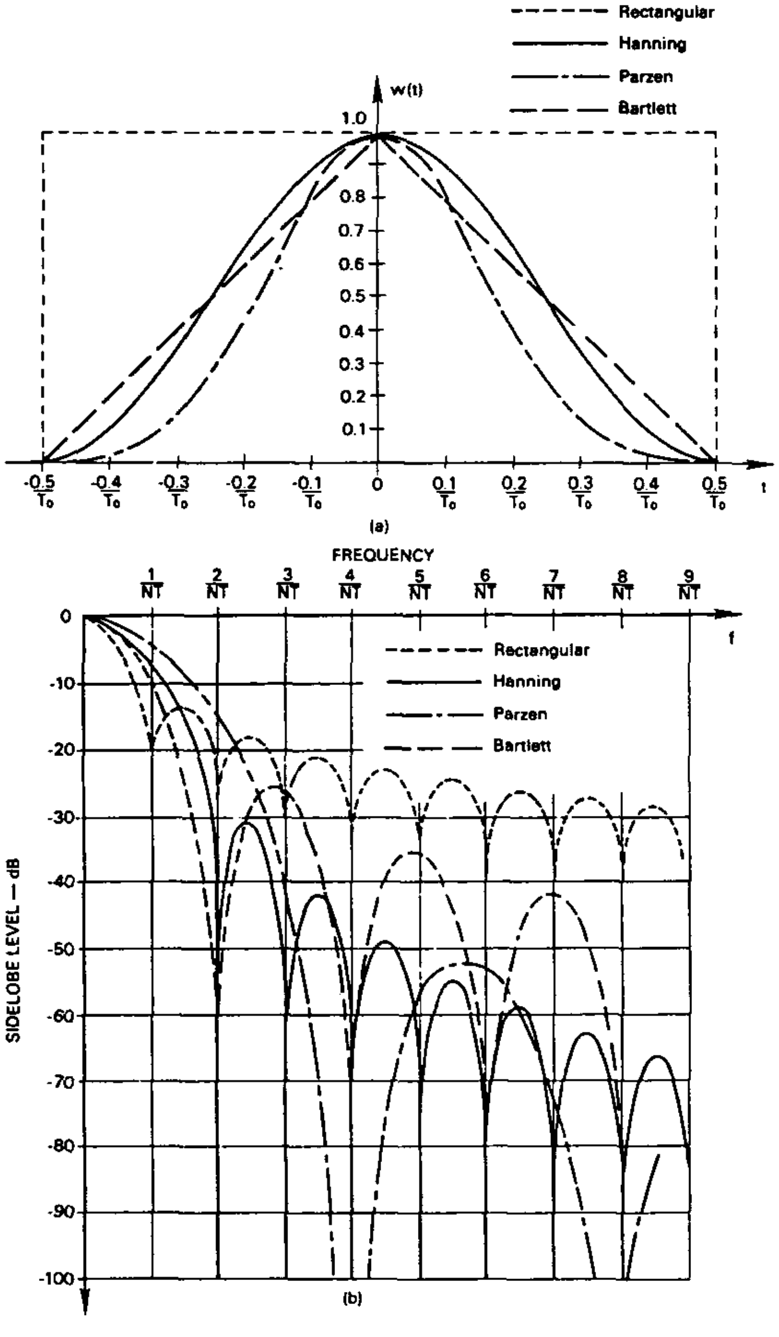

FIGURE 4-10

Fast Fourier Transform weighting or window functions.

Reprinted with permission from Brigham EO: The Fast Fourier Transform. Englewood Cliffs, NJ, Prentice-Hall Inc, 1974, Figure 9-8, p 181.

whenever the analog signal is **sampled.** This means that for any given numerical output of an analog-to-digital converter, there is a limited range of signal inputs, not just a single point. This range is referred to as the **width** of the output code and, in practice, is equal to the least-significant-bit (LSB) of an A-D converter.

Four popular types of A-D converters are available currently in integrated-circuit form. Table 4-4 lists these four types, the signal band width with which they are commonly associated, and some of their attributes. The successive approximation converter with a sample-hold circuit is the most popular for data acquisition systems (Figure 4-11). The method allows great versatility, and recent cost reductions have made it suitable for many applications including EMG. The parallel, flash, or multicomparator ladder design provides the highest speed but usually at the expense of limited resolution (only 6- or 8-bit).

Specifications

In addition to resolution, important specifications for A-D convertors include accuracy, number of channels, maximum sampling rate per channel, and throughput rate. The needs in each of these areas should be determined by the ergonomist when considering the purpose of collecting EMG data.

TELEMETRY

General

A practical problem associated with performing EMG recording in simulated or actual work settings is the requirement that the workers' movements be confined to an area defined by the length of the cable(s) connecting the subject to the recording apparatus. Electrode cables may not exceed a few feet in length without seriously degrading the signal-to-noise ratio of the recording. Electromyographic instrumentation using onsite or centrally located preamplifiers may be used to extend this distance to a maximum of approximately 15 m (50 ft). Although allowing greater mobility, a cable of this length may prove unwieldy or even dangerous, given the mechanized nature of many job sites.

The telemetry of the preamplified EMG signal via radio frequency transmitter and receiver affords the subject untethered movement. An ordinary telemetry link used to transmit electrocardiographic (ECG) information is shown in Figure 4-12. A small battery powered transmitter frequency modulates a radio frequency carrier with the ECG signal that is then broadcast at the carrier frequency. The receiver in turn receives and demodulates the FM signal to recover the ECG information.

Range and Directionality

The range of the telemetry link is determined by the power output capability of the transmitter and the sensitivity of the receiver. As a practical matter, the range of the telemetry equipment is rarely a concern because commercially available battery powered transmitters are capable of transmitting signals that may be received over distances in excess of 30 m (100 ft), a range encompassing the majority of work sites. A larger concern is the directionality of transmitting antennas. Even so called **omnidirectional** transmitting antennas are characterized by weak field strength at various locations in their radiation pattern. The effect of weak field strength on the recovered signal is dependent on the type of modulation employed. In general, it may be understood to effect the signal in the same way as an AM or FM radio broadcast is affected when a radio receiver is positioned at increasing distances from the transmitting antenna. The recovered AM signal becomes weak and noisy while the FM signal is characterized by total signal drop-outs. To reduce the incidence of these problems in telemetry, it is common to use multiple antennas.

Multiple Channel Telemetry

In the majority of applications, a single channel of EMG is inadequate to monitor the muscle groups involved in a work task. The obvious solution is to use multiple transmitter-receiver combinations, each transmitting and receiving at a different frequency. Although this method is used commercially, it is expensive because each component in the system must be duplicated for each additional channel.

A common solution to the problem of multichannel telemetry is to use a form of multiplexing. Multiplexing refers to a system of transmitting several messages simultaneously on the same circuit or channel. Time division multiplexing is not truly simultaneous transmission but rather the sequential transmission of each channel sampled in rapid succession. Because this method incorporates sampling, information loss will occur if the sampling frequency is not several times the product of the number of channels times the bandwidth required.

Frequency division multiplexing is true simultaneous transmission as illustrated in Figure 4-13. Each channel's signal is used to frequency modulate a subcarrier oscillator. The subcarriers are mixed and used to frequency modulate a high frequency oscillator whose output is amplified and transmitted. The receiver is tuned to the high frequency carrier and each band of subcarrier frequencies is band-pass filtered and demodulated to recover the original signal. The table in Figure 4-13 defines the subcarrier bandwidths and center frequencies according

TABLE 4-4

Types, Signal Bandwidth and Attributes of A-D Convertors

Type	Signal Bandwidth	Attributes
Integrating	DC to 100 Hz	high accuracy low speed low cost
Successive approximation	DC to 100 Hz	high speed accuracy at increased cost flexibility
	100 Hz to 1 MHz with sample-hold	
Parallel "flash"	1 MHz + up	highest speed high resolution = expensive
Voltage-to-frequency	DC to 100 Hz	fast responding continuous serial output

to Inter-Range Instrumentation Group (IRIG) standards. Note that the maximum signal that can be transmitted via a particular frequency band is known as the nominal intelligence frequency and is directly proportional to the bandwidth of the subcarrier used.

Telemetry Performance

The performance specifications of telemetry equipment for use with EMG must be judged in the context of the signal information being telemetered. The degree to which the signal is preprocessed before being telemetered will influence the choice of appropriate specifications.

Bandwidth

As discussed previously, the bandwidth of any instrumentation used to amplify or otherwise process EMG must be adequate to preserve the information content of the signal. In the case of raw surface EMG, a bandwidth of 1 to 3000 Hz is recommended as a conservative specification.[14] This specification must also be applied to the telemetry link. Unfortunately, much of the commercially available telemetry equipment marketed for use with human subjects is intended for lower frequency applications such as electrocardiograph and electroencephalograph monitoring. These bioelectric signals are contained in the frequency range of DC to about 150 Hz. Although this bandwidth is inadequate for raw surface EMG, it is more than adequate for processed EMG signals.

Consideration should also be given as to whether signals other than EMG are to be transmitted via the telemetry link. If so, the bandwidth of the telemetry channels assigned to these signals must include the frequency range of the attendant signals. Frequently, variables associated with EMG such as position, force, velocity, and acceleration, are represented by signal frequencies that extend to DC.

Dynamic Range

The dynamic range specification refers to the range of signal amplitudes the telemeterized output may assume without distortion. A small signal amplitude may be characterized by undermodulation and noise. A large signal may be characterized by overmodulation and nonlinear distortion. Ideally, the sensitivity of the system is adjusted to minimize both effects while taking full advantage of the full dynamic range. As no signal may be greater than the limit defined by the dynamic range without distortion, this specification also limits the maximum obtainable signal-to-noise ratio.

Noise and Cross Talk

Noise may be generated within the telemetry equipment itself or from external sources of electromagnetic radiation such as television and radio stations, computers, switching power supplies, and automobile ignition systems. No matter their source, they can play havoc with telemetry signals. Problems of this sort are difficult to predict. One possible solution is to alter the transmitting frequency to an unaffected frequency. This capability is usually provided in commercial designs.

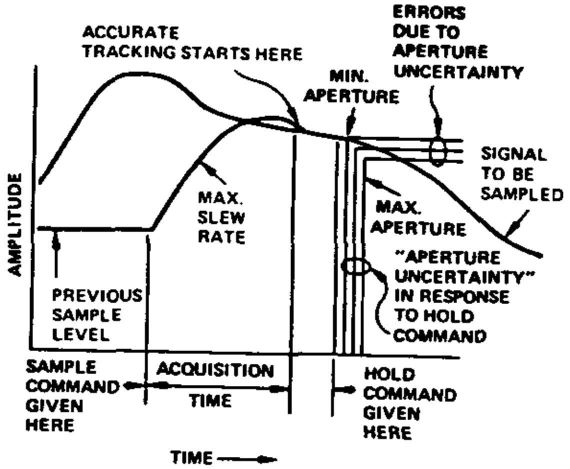

FIGURE 4-11

Sample-hold circuit dynamics and the errors they may create. The time scale is greatly expanded.

Reprinted with permission from the Application of Filters to Analog and Digital Signal Processing. Lockland System Corp, 170 W Nyack Rd, West Nyack, NY, 1976, Figure 25, p 14.

Another problem may appear to be noise but actually is cross talk from an adjacent telemetry channel. Cross talk occurs when an overmodulated signal channel overlaps an adjacent channel. The solution is to prevent the overmodulation by reducing the channel sensitivity.

MONITORS

Always monitor the raw EMG signal for artifacts and noise to ensure the quality and fidelity of the detected waveform. An analog oscilloscope is used typically for this purpose. Because of the wide bandwidth ($\geq$ 1 MHz), excellent linearity, and low noise of most commercial analog oscilloscopes, making an appropriate selection is of little difficulty.

Of more practical concern is choosing an oscilloscope that has the features necessary to make the job of monitoring the raw EMG convenient. In the case of multichannel EMG, it is convenient to display all the channels simultaneously with the same time base. This is accomplished by time-sharing the single beam of the oscilloscope between several channels. By time division multiplexing or chopping the display with sufficient speed, the information content of the individual channels may be preserved.

The quantity of the information displayed on the screen for each sweep of the beam makes some form of short-term storage desirable. The persistence of an ordinary cathode-ray tube display is dependent on the type of phosphor used. The selection of an appropriate phosphor may be used to slightly delay the disappearance of the visual trace without causing confusing superimposition of subsequent traces.

For delays longer than a few fractions of a second, a storage oscilloscope is necessary. Storage oscilloscopes will retain a stored image from a few seconds to several hours, depending on the particular design. The specification of primary importance in selecting an appropriate storage oscilloscope for EMG is stored writing speed. It is recommended the stored writing speed be $\geq$ 0.125 cm/μs.

BIOFEEDBACK

Biofeedback in the context of EMG refers to the presentation of the EMG signal to the research subject as a means of increasing his volutional self-control of specific muscles. The form of the feedback is characteristically visual or auditory. It may consist of anything from the presentation of the raw EMG to the subject in the form of an oscilloscope tracing or as sounds from a loudspeaker to the presentation of a processed signal used to deflect a meter or other indicator.

One popular use of biofeedback in recent times has been the use of auditory feedback of surface EMG for use in relaxation training. In general, however, there are limited applications of EMG biofeedback in ergonomics. In principle, the same instrumentation standards should be applied for use of EMG in these situations. Caution should be exercised in adapting commercial biofeedback instrumentation for use in other measurement applications for which it was not intended. A review of the equipment specifications should reveal if the bandwidth has been reduced or significantly shaped with filters that will actually cause significant signal distortion.

SUMMARY

This chapter presents information about principles of instrumentation applied to the collection of EMG data in an ergonomics setting. Primary emphases are on amplifier characteristics and requirements for processing the EMG into formats that allow the ergonomist to subsequently interpret data. Somewhat detailed information is provided on the topic of frequency domain

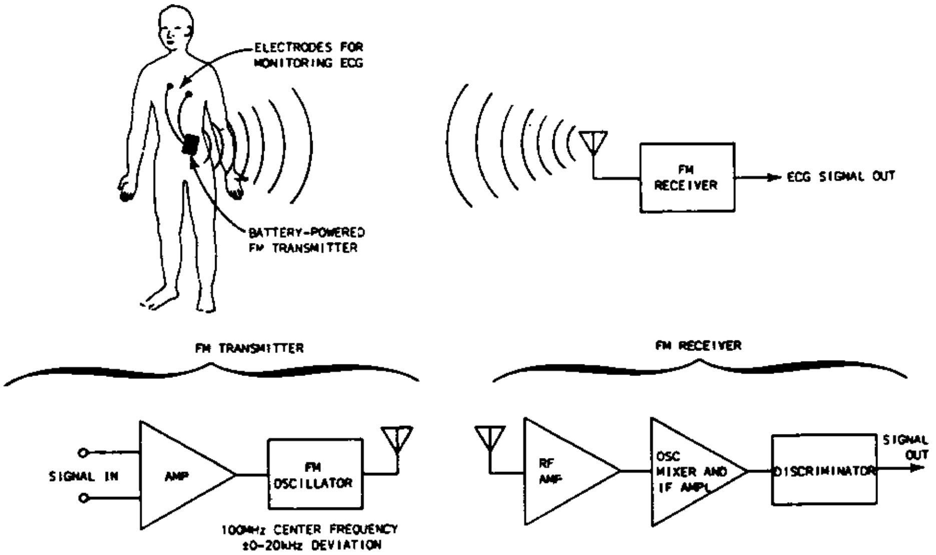

FIGURE 4-12

A typical single-channel telemetry link.

Reprinted with permission from Strong P: Biophysical Measurements. Tektronix, Inc, 1973, Figure 27-1, p 427.

processing has been included because of the potential applications. The topic of recorders or monitors and telemetry and biofeedback are discussed in terms of applications for those interested in applying EMG to the situation where ergonomic questions are of interest.

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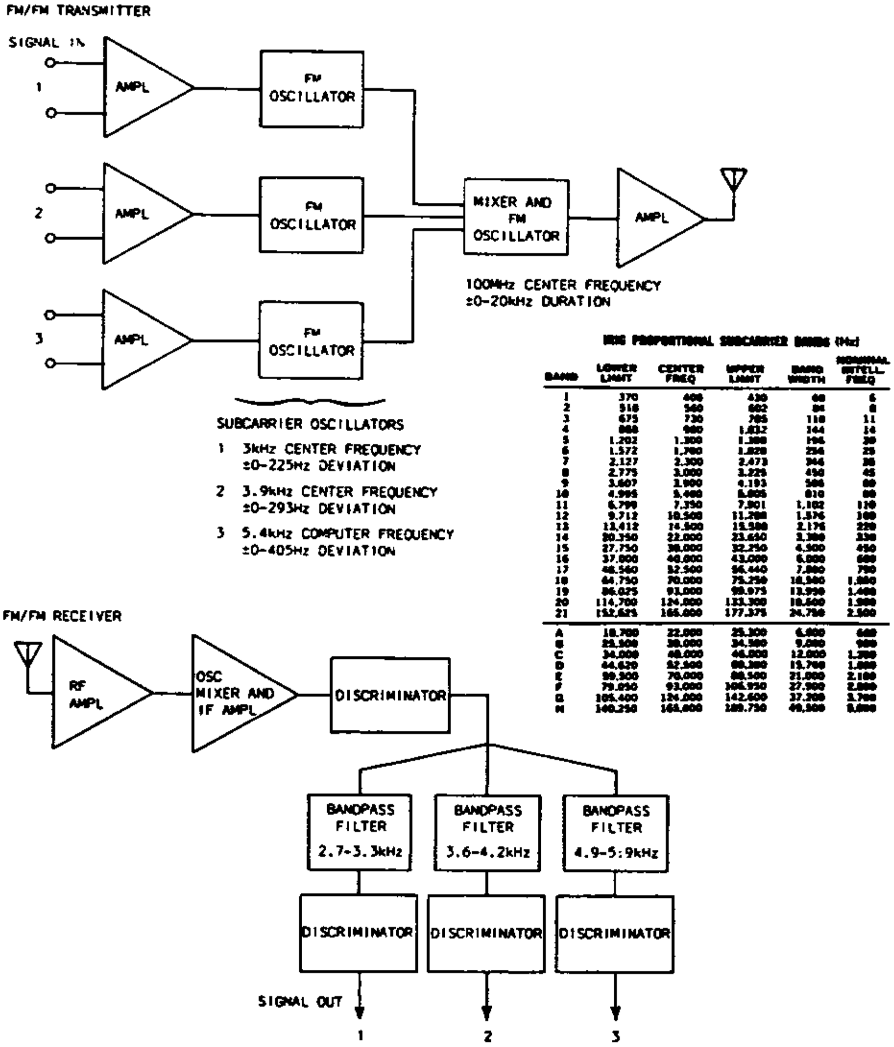

IRIG PROPORTIONAL SUBCARRIER BANDS (Hz)

BAND	LOWER LIMIT	CENTER FREQ	UPPER LIMIT	BAND WIDTH	NOMINAL INTELL. FREQ
1	370	400	430	60	6
2	518	560	602	84	8
3	675	730	785	110	11
4	888	960	1,032	144	14
5	1,202	1,300	1,398	196	20
6	1,572	1,700	1,828	256	25
7	2,127	2,300	2,473	346	35
8	2,775	3,000	3,225	450	45
9	3,607	3,900	4,193	586	59
10	4,995	5,400	5,805	810	81
11	6,799	7,350	7,901	1,102	110
12	9,712	10,500	11,288	1,576	160
13	13,412	14,500	15,588	2,176	220
14	20,350	22,000	23,650	3,300	330
15	27,750	30,000	32,250	4,500	450
16	37,000	40,000	43,000	6,000	600
17	48,560	52,500	56,440	7,880	790
18	64,750	70,000	75,250	10,500	1,050
19	86,025	93,000	99,975	13,950	1,400
20	114,700	124,000	133,300	18,600	1,900
21	152,625	165,000	177,375	24,750	2,500
A	18,700	22,000	25,300	6,600	660
B	25,500	30,000	34,500	9,000	900
C	34,000	40,000	46,000	12,000	1,200
D	44,620	52,500	60,380	15,750	1,600
E	59,500	70,000	80,500	21,000	2,100
F	79,050	93,000	106,950	27,900	2,800
G	105,400	124,000	142,600	37,200	3,700
H	140,250	165,000	189,750	49,500	5,000

FIGURE 4-13

A typical multi-channel telemetry link frequency division multiplexed.

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